Executive Summary
Extracted from

NIST NCSTAR 1-5 (Draft)

Federal Building and Fire Safety Investigation of the World Trade Center Disaster

Reconstruction of the Fires in the World Trade Center Towers (Draft)

EXECUTIVE SUMMARY

E.1 INTRODUCTION

The collapses of the towers in the World Trade Center (WTC) on September 11, 2001, resulted from a combination of aircraft impact damage and the ensuing fires. A prime focus of the National Institute of Standards and Technology (NIST) Investigation was to learn the relative importance of these two factors and their interaction leading to the collapses of the buildings. This entailed such facets as:

- What were the location, magnitude and duration of the fires that brought about the collapses of the WTC towers?
- Were the natures of these fires typical of what might be expected in common occupancies or were there special features that made these fires especially dangerous?
- Could an extreme but conventional fire, occurring without the aircraft impact, have led to the collapse of a WTC tower?

This effort began with the objective to reconstruct, with assessed uncertainty limits, the time-evolving temperature, thermal radiation, and smoke fields in WTC 1, 2, and 7 for use in understanding the behavior and fate of occupants and responders and the structural performance of the buildings. Operationally, this was divided into eight technical tasks:

- Acquisition and application of photographs, videos, and other relevant information to develop detailed time lines for the spread and growth of fires at the peripheries of the WTC buildings.
- Characterization of the types, mass, and distribution of combustibles in the pertinent floors of the WTC buildings at the time of the disaster.
- Location and characterization of the fire endurance properties of the internal partitions (floors, walls, and ceilings) in the pertinent floors of the WTC buildings.
- Determination of the effective thermal properties of the structural insulation systems, the effect of vibration, impact, and shock on their thermal insulation performance, and whether chemical interaction between the insulation materials and the steel at elevated temperatures could degrade the steel and insulation performance during thermal insult.
- Upgrade of the NIST Fire Dynamics Simulator (FDS) for its application to the reconstruction of the fires in the WTC buildings. Development of a computational methodology for mapping the FDS-generated thermal environment onto and through the building's structural elements.
- Conduct of experiments to provide input to and guidance for the FDS combustion sub-model.
- Reconstruction of the gaseous thermal environment surrounding the building's structural elements and the resulting temperature rise within them.

- Generation and use of experimental data for assessing the accuracy of the prediction of thermal insult on structural members such as columns, trusses, beams, and other support structures like those in WTC 1, 2, and 7.

This document reports the likely nature of the fires in WTC 1 and WTC 2 and how NIST was able to reconstruct them. The outcome of the fire reconstructions became a principal input to the assessment of the collapse of the buildings. A reconstruction of the fires in WTC 7 is presented in a separate report.

E.2 PHOTOGRAPHIC EVIDENCE

The destruction of the WTC towers on September 11, 2001, may have been the most heavily photographed disaster in history. This is fortunate since neither of the buildings remained, eliminating access to the telltale signs that fire investigators typically use to assess the path and intensity of a fire. There was a good amount of photographic material shot during the early stage when only WTC 1 was damaged. By the time WTC 2 was struck, the number of cameras and the diversity of locations had increased. Following the collapse of WTC 2, the amount of visual material decreased markedly as people rushed to escape the area and the huge dust clouds generated by the collapse obscured the site.

NIST assembled a collection of nearly 150 segments of video footage (totaling in excess of 300 hours) and over 7,000 photographs. The sources included television networks and stations, the New York City Police Department (NYPD) and Fire Department (FDNY), and assorted World Wide Web sites. The collection included the work of over 200 photographers and 40 videographers. The material was organized into a database in which the searchable properties included the name and location of the photographer, time of shot/video, copyright status, content, whether it included the key events, whether it included FDNY or NYPD people or apparatus, and other details (falling debris, people, building damage).

To construct a time line for fire growth and structural changes in the WTC buildings, times of known accuracy were assigned to the photographic assets. The touchstone was the moment the second plane struck WTC 2, which NIST established from the clocks in the September 11 telecasts as 9:02:59 a.m. Absolute times were then assigned to all frames of videos that showed the second plane strike. By matching photographs and other videos to specific events in these initially assigned videos, NIST staff created a time line extending over the entire day with assigned relative accuracies of ± 3 s or better. The resulting timing of the five major events of September 11 are shown in Table E–1 below.

Table E–1. Times for major September 11, 2001, events.

Event	Time
First plane strike	8:46:30 a.m.
Second plane strike	9:02:59 a.m.
Collapse of WTC 2	9:58:59 a.m.
Collapse of WTC 1	10:28:22 a.m.
Collapse of WTC 7	5:20:52 p.m.

In each photograph and each video frame, each window was coded by whether fire and/or smoke were present and whether the window was still in place or not. Graphical rendering of these results, combined with timed sequencing of the actual photographic frames, led to the construction of highly detailed time lines for the spread of the fires and changes in visible damage to the buildings.

E.3 BUILDING INTERIORS AND COMBUSTIBLES

NIST obtained architectural plans for most of the floors in the impact and fire zones of WTC 1 and WTC 2. These included the locations of interior walls, descriptions of the floor and ceiling construction, and additional features such as the locations of staircases within the tenant spaces.

Since the ceiling system could have served as a temporary protective barrier to heating of the floor structure above, shaking table experiments were conducted to determine the magnitude of building impact that could have led to significant dislodging of ceiling tiles. Forces of the order of 5g caused significant damage to the framing. Since the aircraft impact forces were estimated to have been about 100g, NIST assumed there was not enough of the ceiling system in place to provide significant thermal protection.

The most common floor plan was a continuous open space populated by a large array of workstations or cubicles. Although there were a variety of styles of such units, the cubicles were fundamentally similar. Each cubicle typically was bounded by privacy panels, with a single entrance opening. Within the area defined by the panels was a desktop, file storage, bookshelves, carpeting, chair, etc. Presumably there were a variety of amounts and locations of paper, both on the work surfaces and within the file cabinets and bookshelves. These cubicles were grouped in clusters or rows, with up to 215 units on a given floor.

NIST conducted fire tests of single representative workstations, both to obtain flammability data and to provide input for a combustion algorithm for FDS. The tests included the effects of the presence of jet fuel and of fallen inert material representative of ceiling tiles or wall fragments. The results were:

- A workstation generated a total heat release of approximately 3.9 GJ from a mass loss of approximately 200 kg. These values were insensitive to the addition of jet fuel or inert material. Approximately 75 percent of the heat release and mass loss occurred over a period of approximately 20 min. The peak heat release rate (HRR) was approximately 7 MW.

- The inert material reduced the peak HRR approximately in proportion to its coverage of the burning surfaces.

- The jet fuel sharply shortened the time to involvement of all accessible combustible surfaces, and thus the time to the peak HRR.

From the floor plans and the combustibility data, it was estimated that the fuel load in the WTC tenant spaces was approximately 20 kg/m^2 (4 lb/ft^2). The two aircraft introduced significant increments to this fuel loading along the paths of their entry into the buildings. United Airlines, American Airlines, and Boeing (the manufacturer of the two hijacked aircraft) provided information on the combustibles that the aircraft brought into the respective buildings.

Insulation against damaging temperature rise in the structural elements was accomplished using a combination of sprayed fire resistant materials (SFRMs) and gypsum wallboard. NIST measured the cohesive strength of the dominant SFRM and its adhesive strength to steel substrates with and without primer. NIST also obtained samples of the two types of sprayed insulation and four types of gypsum wallboard and sent them to testing laboratories for determination of their thermal conductivity, density, and heat capacity, all as a function of temperature from ambient. The sprayed material data were for 25 °C to 1,200 °C; the wallboard data were from 25 °C to 600 °C.

The thermal protection afforded by SFRMs is typically obtained under steady and uniform heating conditions in a test furnace such as that prescribed in the ASTM E 119 standard for fire resistance ratings. Actual fires can reach high irradiances faster, are generally not isotropic, and may wane and re-grow before running out of fuel or being extinguished. NIST conducted a series of experiments in the NIST Large-scale Fire Laboratory to obtain data on SFRM performance under realistic fire conditions. Within a large test compartment, an assortment of representative steel members were exposed to controlled fires from steady-state gas burner fires of different heat release rate and radiative intensity. The steel members were bare or coated with SFRM in two thicknesses. The thermal profile of the fire was measured at multiple locations within the compartment. Temperatures were also recorded at multiple locations on the surfaces of the steel, the insulation, and the compartment. The results were then used to guide the fire modeling effort.

E.4 FIRE MODELING

The required output of the simulations of the fires in the WTC towers was a set of three-dimensional, time varying renditions of the thermal and radiative environment to which the structural members in the tower were subjected from the time of aircraft impact until their collapses. These profiles were generated using the NIST FDS, a computational fluid dynamics model of fire-driven fluid flow with which NIST had extensive experience. FDS represents the space(s) in which the fire and its effluent are to be modeled as a grid of rectangular cells. The fire generates hot gas, which radiatively and convectively heats the surfaces of walls and combustibles. The rate at which each combustible generates combustible vapor depends on this heat flux to the surface and the fuel's effective heat of gasification. To create burning, FDS assumes that combustion occurs at the interface of two (adjacent) grid cells, when the first cell contains more air than is needed to combust the vaporized fuel within that cell and the second cell contains less air than is needed to combust the fuel within (the second) cell.

FDS predictions of the thermal environment in the steel exposure tests were generally within experimental uncertainty:

- The predicted upper layer gas temperatures were within 4 percent of the measurements.
- There was good agreement with measured gas velocities at the compartment inlets.
- Because of limited spatial resolution at the outlet window, the steep gradient in velocity was not captured by the model, but the integrated mass flux was.
- FDS predicted the leaning of the fire plume caused by asymmetric obstructions in the compartment, but underestimated the extent of the leaning. This adversely impacted predictions of the thermal behavior of structural components at some locations near the fire.
- The predictions of radiative heat fluxes in the upper layer were within 10 percent of the measurements.

- FDS predictions of the heat flux to the floor and column surfaces facing the fire were good; less so for the surfaces facing away due to the underprediction of the flame leaning.

In these experiments, the "fire" was a steady heat source whose combustion properties were steady and well known. The comparison between experiment and calculation was thus a test of the fluid mechanics and heat transfer capability in FDS. The good agreement indicated that no changes were needed in these aspects of FDS.

Capturing the behavior of the single workstation fires involved the additional features of a complex burning object. Data on the combustion of the combustible components of the workstation were obtained using a Cone Calorimeter (ASTM E 1354), with the test specimens exposed to varying incident heat fluxes and piloted ignition of the vapors. Predictions of the workstation combustion using these data were not satisfactory because (a) there were some features of the combustion that would be difficult for a simulation of current capability to capture (e.g., complex burning of the chair, ash formation from stacks of exposed paper, falling items that led to changes in the geometry of combustibles) and (b) some of the workstation components ignited from irradiance alone.

Thus a modified combustion approach was implemented. The carpet, desk and privacy panel data from the Cone Calorimeter were used as originally planned. The remaining components were represented as homogeneous "boxes," which were assigned a burning rate. The prediction quality was much improved:

- The magnitudes of the peak HRR values were within 10 percent of the experimental values.
- The shape and magnitude of the subsequent, near-steady burning behavior were quite similar.
- The overall burning times were similar for the experiments and the simulations.
- The effects of the tiles in decreasing the peak HRR and the jet fuel in increasing the peak HRR and on the subsequent burning behavior were captured correctly.

However, the peak HRR in the simulations without jet fuel occurred sooner than in the experiments, a result of lumping the chair together with various other combustible items. In addition, the simulations underpredicted the large reduction in the time to the peak HRR for the addition of jet fuel.

Nonetheless, the chosen set of parameters and approximated component burning descriptions gave a reasonable description of the actual workstation HRR behavior and its dependence on the inert material coverage and presence of jet fuel. The localized differences between the simulations and experiments would become less important when several (or more) workstations were burning concurrently, as was the case in the large fires on September 11.

A third set of fire tests was then conducted to assess the accuracy with which FDS predicted the fire spread, heat release rate, and thermal environment in a large compartment in which three workstations were burning in a compartment configuration characteristic of that found in the WTC buildings. Again the effects of the presence of inert material and jet fuel were included, as was the effect of different degrees of "rubblizing" the furniture. In these tests:

- The total mass loss was triple the mass loss from the single workstations tests.

- The peak HRR values were only about 50 percent higher than the single workstation burns, reflecting the ventilation-limited nature of the three-workstations tests. This is consistent with the HRR peaks being independent of the location of the fire in the compartment.

FDS simulation of each test was carried out before the test was conducted. The quality of the simulations was deemed satisfactory:

- The shapes and magnitudes of the predicted and measured HRR curves were close.
- The predicted times to the peak HRR region were within about a minute of the measured rise times. FDS captured the significant decrease in time to the peak HRR region due to the jet fuel.
- The predicted peak HRR values were within experimental uncertainty of the measured values.
- FDS consistently overpredicted the HRR in the region following the HRR peak. Repeating the simulations with an increased heat of gasification of the "box" combustibles greatly improved the fit, but at the expense of underpredicting the peak intensity. As a result, the decision was made to use the higher heat of gasification value in further simulations.
- The prediction of the HRR of the rubblized furniture required only one adjusted parameter: since the mass loss was half that of the assembled workstations, the burning rate for the simulation was reduced by the same factor. Thus, this factor was used in the reconstruction of the WTC fires in the regions where highly damaged furnishings were expected.

In an assessment of the model, it is important to maintain perspective on the accuracy required to reconstruct the actual WTC fires. For fires that were sufficiently severe that they threatened the structural integrity of the building, many workstations burned concurrently. These workstations were at various stages of their combustion and the aggregate burning of a large group of workstations would average out features that are not precisely modeled, which should improve model accuracy.

E.5 HEAT TRANSFER MODELING

Simulating the effect of a fire on structural integrity requires a means for transferring the heat generated by the FDS-simulated fire to the surface of the structural members and then conducting the heat through the (insulated) columns, trusses and other elements that made up the tower structure. This process was made difficult for these large, geometrically complex buildings by the wide disparity in length and time scales that had to be taken into account in the simulations.

To overcome these difficulties, NIST developed the Fire Structure Interface (FSI). To use the FSI with a set of FDS-calculated gas phase temperatures:

- The compartment was divided into a hot, soot-laden upper layer and a cool, clear lower layer.
- Explicit formulae for the radiative heat flux were obtained as a function of temperature, hot layer depth, soot concentration and orientation of each structural element.

- Structural components in the hot layer were also subject to convective fluxes based on the difference between their surface temperature and the local hot layer temperature.

- The thermophysical properties of the steel in the structural elements and of the SFRM were obtained from published data and new data developed under the Investigation.

- The resulting data set was subsequently read into the ANSYS 8.0 finite element program, which generated the thermal distribution within the structural elements.

The "transparency" of FSI was estimated by comparison of FDS-FSI predictions of steel and SFRM surface temperatures with those obtained in the steel element exposure tests. The FSI appeared to add little to the overall uncertainty in the simulation of the temperatures at the outer surfaces of bare steel elements and the surfaces of SFRM and, more importantly, at the SFRM-steel interface. On the average, the numerical predictions of the steel surface temperature were within 7 percent of the experimental measurements for bare steel elements and within 17 percent for the insulated steel elements. The former was determined to result from uncertainty in the heat release rate in the fire model. The increase in the latter was attributed to model sensitivity to the SFRM coating thickness and thermal conductivity.

E.6 RECONSTRUCTED FIRES

The simulations of the fires and of their heating of the building structure were the second and third computational steps, respectively, in the identification of the probable sequences leading to the collapses of the towers. They followed the simulation of the aircraft impacts and preceded the analysis of the behavior of the damaged and heated building structure.

After a number of simulations to gain insight into the factors having the most influence on the nature of the fires, for each tower, two fire scenarios (Case A and Case B for WTC 1 and Case C and Case D for WTC 2) were superimposed on two aircraft-driven damage patterns. For each of the four scenarios, FDS was used to generate a time-dependent gas temperature and radiation environment on each of the floors. The following apply to all the Cases:

- Eight floors were modeled in WTC 1 (92 through 99) and six floors were modeled in WTC 2 (78 through 83). Each floor was modeled separately, since examination of the photographic collection indicated little evidence for floor-to-floor fire spread in the short times that the towers survived. Heat conduction through the floors was included.

- Detailed floor plans were available for the eight modeled floors in WTC 1 and the 80th floor of WTC 2. For the remaining floors in WTC 2, the layouts were estimated from the architectural drawings of the core space and from recollections by Port Authority staff and workers from the tenant spaces.

- The condition of the interior walls, whether intact or damaged by the aircraft debris, did not change during a fire simulation.

- The furnishings not in the debris path were assumed to be undamaged and were modeled as developed from the experiments mentioned above. Those furnishings deemed to be rubblized were assigned two-thirds the burning rate of the undamaged furnishings.

- During a simulation, windows were removed at the time indicated in the photographs.
- Vertical shafts in the core area were incorporated as shown in the architectural drawings. For undamaged floors, all the openings to the core area were assumed to total 5 m^2 in area.
- It was assumed that 40 percent of the jet fuel was available for combustion on the impact floors. The distribution was derived from the aircraft impact modeling.
- The mass of combustibles in each aircraft was obtained from the airlines and the aircraft manufacturer.
- In the FDS computational grid, each floor comprised 128 by 128 by 9 cells. Each cell was 0.5 m in width and depth and 0.4 m in height.
- Prior to aircraft impact, the SFRM was assumed to be consistent with the as-built condition and characterized by a uniform equivalent thickness. If a structural element was found to be in the path of a debris field of sufficient intensity, all the insulation (SFRM and gypsum board) was deemed to have been removed.
- Core walls impacted by sufficiently energetic debris were fully removed. This enabled rapid venting of combustion gases into the core shafts and reduced the burning rate of combustibles in the tenant spaces. In cases B and D, a more severe representation of the damage was to leave a 1.2 m soffit that would maintain a hot upper layer on each fire floor. This produced a fire of longer duration near the core columns and the attached floor membranes.

Sensitivity tests identified those factors that were the most influential on the outcome of single floor FDS simulations. Table E–2 summarizes how those factors were incorporated into the four Cases.

Table E–2. Values of WTC fire simulation variables.

Variable	WTC 1		WTC 2	
	Case A	**Case B**	**Case C**	**Case D**
Fuel load	20 kg/m^2 (4 lb/ft^2)	25 kg/m^2 (5 lb/ft^2)	20 kg/m^2 (4 lb/ft^2)	25 kg/m^2 (5 lb/ft^2)
Distribution of disturbed combustibles	Even	Weighted toward the core	Heavily concentrated in the northeast corner	Moderately concentrated in the northeast corner
Condition of combustibles	Undamaged except in impact zone	Displaced furniture rubblized	All rubblized	Undamaged except in impact zone
Representation of impacted core walls	Fully removed	Soffit remained	Fully removed	Soffit remained
Structural damage, NIST NCSTAR 1-2[1] Case	Base	More severe	Base	More severe
Insulation damage, NIST NCSTAR 1-2 Case	Base	More severe	Base	More severe

1 This reference is to one of the companion documents from this Investigation. A list of these documents appears in the Preface to this report.

The results of the FDS simulations of the perimeter fires were compared with the fire duration and spread rate as seen in the photographs and videos. A sample of the basis for such a comparison is shown in Figure E–1. This depicts the room gas temperature 0.4 m below the ceiling slab (in the "upper layer" of the compartment). Surrounding this are "stripes," each representing a window on that floor. Black stripes denote broken windows, orange stripes denote windows where flames have extended outward from the building, and yellow stripes denote fires that were seen inside the building. Fires deeper than a few meters inside the building could not be seen because of the smoke obscuration and the steep viewing angle of nearly all the photographs.

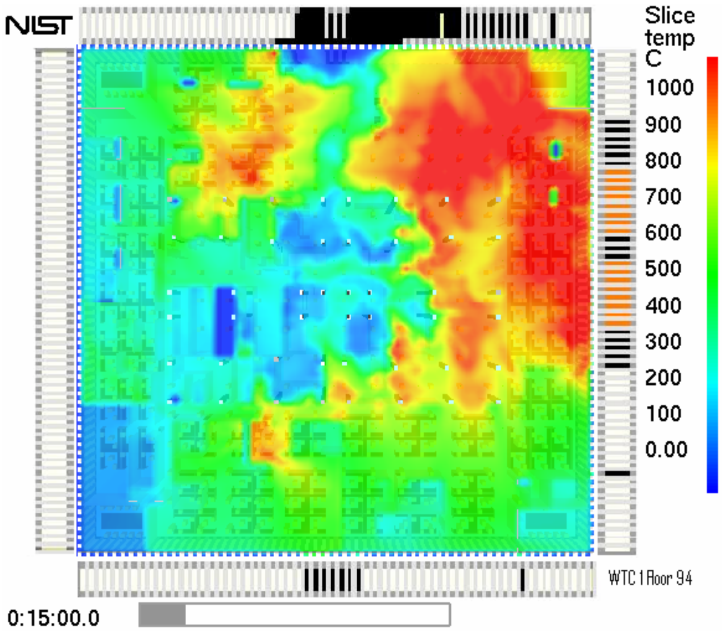

Figure E–1. Upper layer temperature of WTC 1, floor 94, 15 min after impact.

In WTC 1, much of the fire activity was initially in the vicinity of the impact area in the north part of the building, then it spread around the east and west faces, and was last observed to be concentrated in the south part of the building at the time of collapse. The fact that the simulated fires encircled the building in roughly the same amount of time as the actual fires supported the estimate of the overall combustible load of 20 kg/m^2 (4 lb/ft^2). Simulations performed with higher loads required a proportionately longer amount of time to bring the fires around to the southeast because of the fact that the burn time was roughly proportional to the fuel mass in the oxygen-limited interior of the fire floors.

For WTC 2, relying mainly on Case D, there was less movement of the fires. The major burning occurred along the east side, with some spread to the north.

Much of the information needed to simulate the fires as described above came from laboratory-scale tests. While some of these involved enclosures several meters in dimension and fires that reached heat release rates of 10 MW and 12 GJ in total heat output, they were still far smaller than the fires that burned on September 11, 2001, in the WTC towers. Figure E–2 shows the heat release rates from the FDS simulations of the WTC fires. The peak plateau heat release rates were about 2 GW for WTC 1 and 1 GW for WTC 2. Integrating the area under these curves produced total heat outputs from the simulated fires of about 8,000 GJ from WTC 1 and 3000 GJ from WTC 2. That adequate representations of disasters can be generated using data from experiments two orders of magnitude smaller is an indication of the capability within the fire research community.

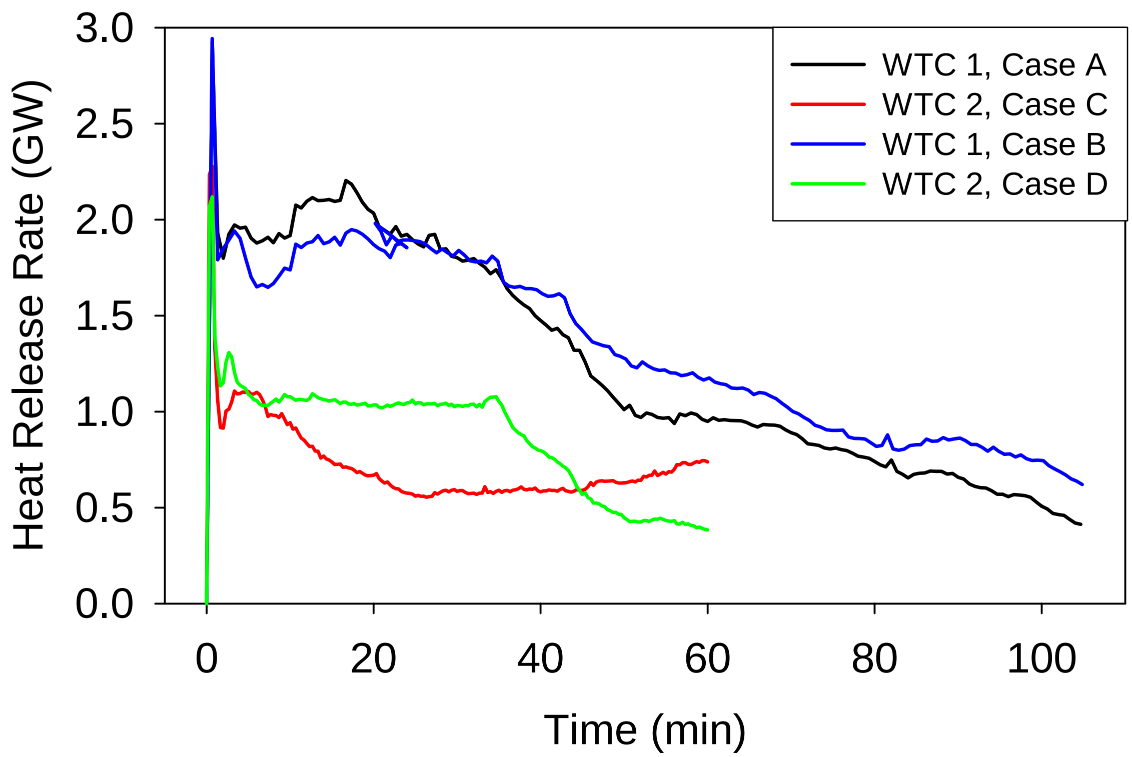

Figure E–2. Predicted heat release rates for fires in WTC 1 and 2.

The results of the fire simulations were used in detailed calculations of the temperature histories of the structural components. The data from FDS were processed and used as boundary conditions for the finite-element calculation of the structural temperatures. Four quantities were transferred from FDS:

- The upper and lower layer gas temperatures, time-averaged over 100 s and spatially-averaged over 1 m. The upper layer gas temperatures were taken 0.4 m (one grid cell) below the ceiling. The lower layer temperatures were taken 0.4 m above the floor.
- The depth of the smoke layer, estimated from the vertical temperature profile.
- The absorption coefficient of the smoke layer 0.4 m below the ceiling.

The FSI was then used to “map” these onto and within the structural elements. Critical to the accuracy of this step was the status of the structural insulation following the aircraft impact. Figure E–3 shows a typical damage diagram generated from the Investigation's aircraft impact modeling and confirmed, where possible, using photographs and videos. Structural changes that occurred later, due to the fires, were not included. In the FSI computations, the concrete slab, trusses or core beams in the areas marked by the red rectangles were removed. Figure E–4 depicts the structural steel thermal data generated by FSI. Similar data were generated for the concrete floor slab.

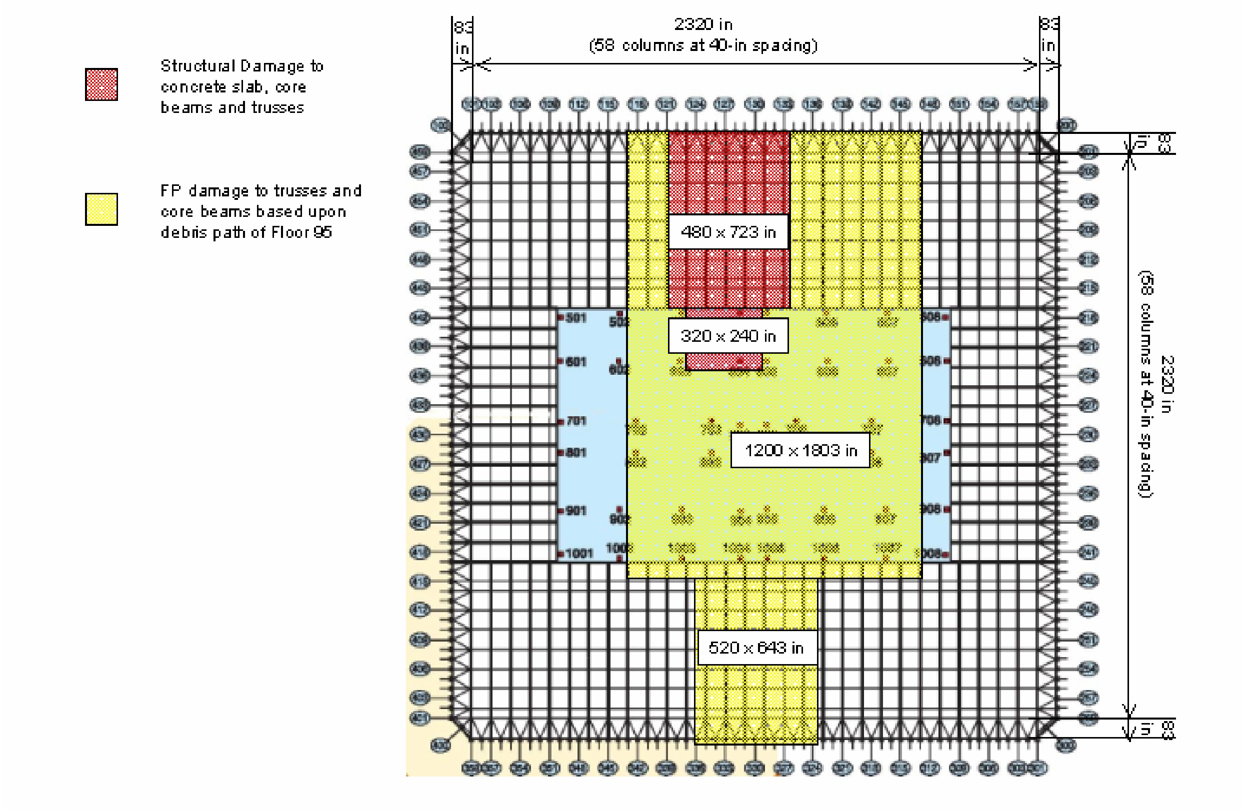

Figure E–3. Structural and insulation damage to Floor 96 of WTC 1, Case B.

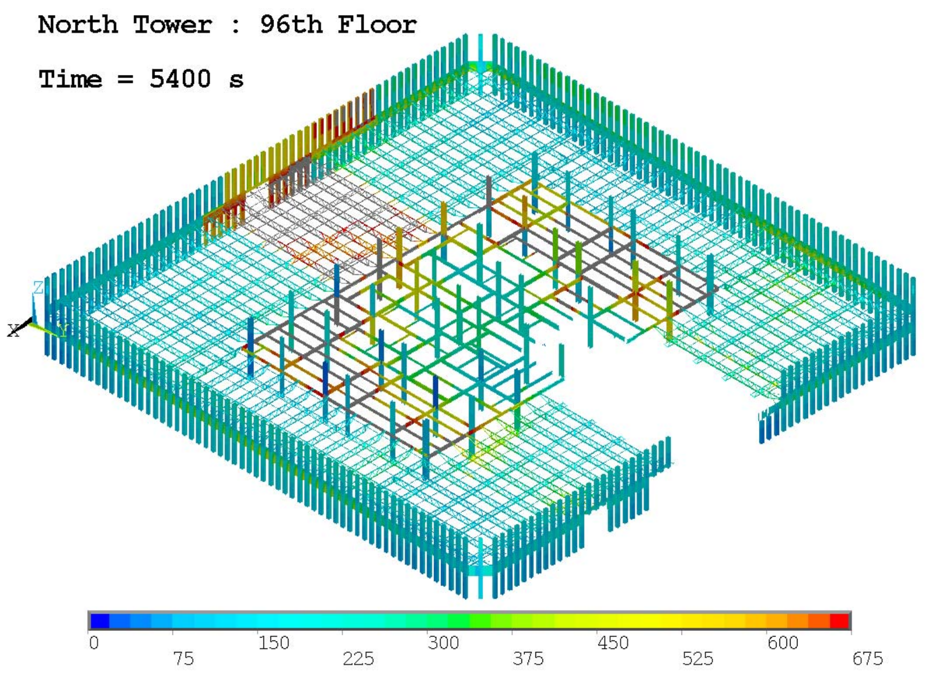

Figure E–4. Thermal response of Floor 96 of WTC 1 at 5,400 s after impact, Case B.

The thermal data files then became input for the analysis of the changes in structural performance that resulted from exposure to the fire environments. The FSI calculations were performed at time steps ranging from 1 ms to 50 ms. Use of the resulting data set for structural analysis would have required a prohibitive amount of computation time. Thus, for each Case, the instantaneous temperature and temperature gradient for each grid volume was provided at 10 min intervals after aircraft impact. For WTC 1, there were 10 such intervals, ending at 6,000 s; for WTC 2 there were 6 intervals, ending at 3,600 s. The data files were in a format consistent with ANSYS 8.0.

E.7 FIRE IN AN UNDAMAGED BUILDING

After incurring the direct damage from two different aircraft strike conditions, WTC 1 and WTC 2 stood for 102 min and 56 min, respectively. Structural models of the two aircraft-damaged buildings indicated that, in the absence of weakening by fires or other substantial insult, the buildings would have continued to stand indefinitely. The application of the fire scenarios in Cases B and D to the aircraft-damaged towers led to collapse.

To complete the assessment of the relative roles of aircraft impact and ensuing fires, NIST examined whether an extreme but conventional fire, occurring without the aircraft impact, could have led to the collapse of a WTC tower, were it in the same condition as it was on September 10, 2001.

The characteristics of such a maximum credible fire could have been:

- Ignition on a single floor by a small bomb or other explosion. If arson were involved, there might have been multiple small fires ignited on a few floors.
- Air supply determined by the building ventilation system.
- Moderate fire growth rate. In the case of arson, several gallons of an accelerant might have been applied to the building combustibles, igniting the equivalent of several workstations.
- Water supply to the sprinklers and standpipes maliciously compromised.
- Intact structural insulation and interior walls.

The four cases described in this report represented fires that were far more severe than this:

- The incident jet fuel created large and widespread early fires on several floors.
- The aircraft and subsequent fireballs created large open areas in the building exterior, though which air could flow to support the fires. In Case A, the fire was still limited by the total vent area (broken windows plus aircraft gash). In Case C, the fire had sufficient air. The fires in both Cases were immense.
- About 10,000 gal of jet fuel were sprayed into multiple stories, simultaneously igniting hundreds of workstations.
- The impact and debris removed the insulation form a large number of structural elements that were then subjected to the heat from the fires.

In the simulations of these four cases, none of the columns and trusses for which the insulation was intact reached temperatures where significant loss of strength occurred.

E.8 FINDINGS

E.8.1 Characteristics of the Buildings

- The floors which the aircraft impacted, and on which the major fires occurred, were mostly occupied by a single tenant. The floor plans were generally open, with few interior walls.

- The principal combustibles on the fire floors were workstations, each capable of generating a peak heat release rate 7 MW and a total (integrated) heat release of 4 GJ. The total fuel load on the WTC floors was low, about 4 psf, 20 kg/m^2.

- The aircraft added significant combustible material to their paths (and the paths of their breakup fragments) through the buildings.

- The ceiling tile systems in the fire zones were heavily damaged by the shocks from the aircraft impacts and would have provided little, if any, barrier to fire exposure of the ceiling structure. This was consistent with multiple observations during the evacuation.

E.8.2 Characteristics of the Fires

- Upon aircraft impact, a significant fraction of 10,000 gal of jet fuel ignited within the building. The expansion of the hot combustion gases broke windows and blew some of the remaining fuel through them in large fireballs.

- The jet fuel fires consumed most of the oxygen within the fire floors, and the fires quickly died down. The fires grew as fresh air became available and the primed solid combustibles reached their full burning rates.

- The jet fuel was the primer for near-simultaneous ignition of larges fires on multiple floors.

- The dominant fuel for the fires in the towers was the office combustibles. On the floors where the aircraft fuselage impacted, there was a significant, but secondary contribution from the combustibles in the aircraft. Most of the jet fuel in the fire zones was consumed in the first few minutes after impact, although there may have been unburned pockets of jet fuel that led to flare-ups late in the morning.

- The major fires in WTC 1 were on the 93rd through 99th floors. The fires generally moved both clockwise and counterclockwise form the north to the south of the tenant spaces. The fires were generally ventilation limited, i.e., they burned and spread only as fast as fresh air became available, generally from additional window breakage.

- The major fires in WTC 2 were on the 79th through 83rd floors, with the most important fires being in the northeast corner of the 81st and 82nd floors. The fires moved far less than those in WTC 1, remaining in the east half of the floors. The fires had sufficient air to burn at a rate determined by the properties of the combustibles. This was in large part due to the extensive breakage of windows in the fire zone by the aircraft impact.

- At the time of the building collapses, there were still vigorous fires, indicating the unchecked fires could have burned for well over an hour.

E.8.3 Capability for Large Fire Reconstruction

- It was possible to reconstruct a complex fire in a large building, even if the building is no longer standing. However, this required extraordinary information to replace what might have been gleaned from an inspection of the post-fire premises. In the case of the WTC tower, this information included floor plans of the fire zones, burning behavior of the combustibles, simulations of damage to the building interior, and frequent photographic observations of the fire progress from the building exterior.

- Proper design and interpretation of laboratory fires over two orders of magnitude smaller (heat release rates of 10 MW and 12 GJ in total heat output) than the WTC fires provided valid information for simulating the WTC fires.

- Conventional office workstations reached a peak burning rate in about 10 min and continued burning for a total of about a half hour. Partial covering of surfaces with inert material reduced the peak burning rate proportional to the fraction covered, but did not affect the total amount of heat release during the entire burning.

- Jet fuel sprayed onto the surfaces of typical office workstations burned away within a few minutes. The jet fuel accelerated the burning of the workstation, but did not affect the overall heat released.

- The FDS was capable of prediction of the room temperatures and heat release rate values for complex fires to within 20 percent, when the building geometry, fire ventilation, and combustibles were properly described. Parallel processing was essential to keep computation times tractable.

- The Fire Structure Interface, developed for this Investigation, was able to map the fire-generated temperature and radiation fields onto and through layered structural materials to within the accuracy of the fire-generated fields and the thermophysical data for the structural components.

E.8.4 Simulations of the WTC Fires

- Insulation damage due to the aircraft impact was the single most important parameter affecting whether a structural member reached a temperature range likely to cause loss of structural strength.

- The plateau heat release rates from the fires were about 2 GW for WTC 1 and 1 GW for WTC 2. The total heat outputs were about 8,000 GJ from WTC 1 and 3,000 GJ from WTC 2.

- For fires of this magnitude, the important factors in determining burning rates were the ventilation area and location, the mass loading of the combustibles, their spatial distribution, and their heats of gasification. The presence of high volatility materials, such as jet fuel, were instrumental during the initiation phase, but mostly burned away rapidly and (except for a few flare-ups observed in WTC 2) played little or no role later.

- A very severe, conventional, multi-story fire would not have heated the structural steel components of the towers to temperatures where significant loss of strength occurred, if the components were insulated at the average thicknesses specified for the towers.